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Reconfiguring the RUM Experiment To Test Circular Scanning With Rotating Unbalanced-Mass Devices on Gimbaled Payloads

M. E. Polites
and D. C. Alhorn

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M. E. Polites
and D. C. Alhorn
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

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TECHNICAL PAPER

RECONFIGURING THE RUM EXPERIMENT TO TEST CIRCULAR SCANNING WITH ROTATING UNBALANCED-MASS DEVICES ON GIMBALED PAYLOADS

I. INTRODUCTION

Some space-based, ground-based, and balloon-borne science instruments require scanning to meet their scientific objectives. For example, see references 1 and 2. With some of these, the only possible way to achieve the required scan motion is to gimbal and scan the entire instrument, as with x-ray and gamma-ray instruments. Three types of scan patterns are commonly desired. One is the line scan, characterized by the instrument line-of-sight repeatedly moving back and forth in a line centered on a target. A second is the raster scan, which is like the line scan except with some slow complementary motion in the direction perpendicular to the scan line. This motion could be stepping, constant velocity, or saw-toothed. A third is the circular scan, characterized by the line-of-sight repeatedly tracing out a circle centered on the target. References 3 and 4 present a new scheme for scanning such payloads, one that offers significant power savings in the right applications. This scheme relies on the centrifugal force from a pair of rotating unbalanced-mass (RUM) devices to produce the scan motion. To verify this approach, an experiment will be constructed which generates line, raster, and circular scans for a gimbaled payload with a pair of RUM devices. Reference 5 describes this experiment, configured to generate the line and raster scans. This paper describes this same experiment, but reconfigured to generate the circular scan. A description of the experiment and the servos designed to control it is given. A computer simulation model of the total system is discussed, and simulation results are presented that predict system performance and verify the control system design.

II. DESCRIPTION OF THE EXPERIMENT

The mechanical configuration of the RUM experiment for circular scanning is identical to that for line and raster scanning, except the RUM devices are mounted differently. The RUM experiment consists of an emulated payload mounted in a two-axis, elevation/cross-elevation gimbal system as illustrated in figure 1. The two RUM devices are mounted at opposite ends of the payload and arranged to produce circular motion when the RUM's are driven at a constant rate and maintained 180° out of phase. Each RUM has mass m = 0.155 slugs, on a lever arm r = 0.5 ft, mounted at a distance d = 2.5 ft from the center-of-mass of the payload. These parameters, along with the RUM angle θ_R, are defined in figure 2. The payload is a steel I-beam with dimensions 6 in by 6 in by 6 ft, weighing about 170 lb. The moments of inertia for the I-beam about the elevation and cross-elevation axes are approximately $I = I_E = I_X$ = 16.3 slug-ft^2, respectively. The payload scan frequency is the same as the frequency of rotation of the RUM devices, in cycles/s or Hz. The radius of the scan circle is determined from the formula,

$$\theta_M = \frac{2 \cdot m \cdot r \cdot d}{I} ,$$

where θ_M is the scan radius in rad.[4] Hence, for the parameters given, $\theta_M = 0.024$ rad or 1.4°. The function of the gimbal servos on the cross-elevation and elevation axes is to keep the center-of-scan from drifting in these axes.

Initially, the elevation angle will be positioned to $\theta_E = -90°$ and the RUM's will generate a circular scan to emulate scanning in a zero-g environment. Figure 3 describes the elevation and cross-elevation gimbal angles, θ_E and θ_X respectively, in relation to the gravity vector $\boldsymbol{g}$. Once this has been demonstrated, the elevation angle will then be positioned to $\theta_E = 0°$ and the procedure repeated. Scanning at $\theta_E = 0°$ is the most difficult situation because the disturbance torques due to gravity on the RUM masses reach their absolute maximum. For a given elevation angle, cross-elevation angle, and RUM angle, the disturbance torque is approximately:

$$T_D = \pm m \bullet g \bullet r \bullet [\theta_X \bullet \sin(\theta_E) \bullet \sin(\theta_R) - \cos(\theta_E) \bullet \cos(\theta_R)],$$

where the + and – signs apply to RUM No. 1 and RUM No. 2, respectively. The acceleration-of-gravity constant has a value of approximately $g \approx 32.2$ ft/s^2. Hence, at $\theta_E = \theta_R = 0°$, the disturbance torque achieves a maximum value of : $T_{DM} = m \bullet g \bullet r = 2.5$ ft-lb.

III. DEFINITION AND DESIGN OF THE SERVOS UTILIZED IN SCANNING

The servos in the RUM experiment configured for circular scanning are like those for line and raster scanning; only the algorithms that generate the servo commands are slightly different. Since the RUM's are mounted differently, the disturbance torque due to gravity on each RUM mass changes which in turn changes the feed forward compensation commands in the RUM servos. In the elevation servo, the gimbal angle and rate commands are now sinusoidal, similar to the cross-elevation commands, but shifted 90° in phase to generate the circular scan profile.

The following description of the servo components and the control parameters has not changed from those for line and raster scanning in reference 5. It is repeated here for completeness.

There are four separate servos—one for each RUM device and one for each gimbal. All four are implemented by a single microcontroller which is the primary component of the electronic-hardware block diagram as shown in figure 4. The microcontroller, an INTEL 80C196KB, performs all the control law computations, while the host computer is used only to program, initialize, and change parameters in the microcontroller during operation. No calculations are performed by the host computer during operation of the RUM experiment.

Each servo has the same basic configuration and components as shown in the shaded portion of figure 4. The microcontroller sends an eight-bit control command to an IXYS IXDP610 pulse-width modulation (PWM) integrated circuit (IC). The IXDP610 outputs a corresponding PWM signal for the power amplifier. The power amplifier receives the PWM signal and generates the current necessary to drive the motor.

The motors are rare-Earth brush type INLAND motor/tachometer units with a motor constant $K_M = 0.61$ ft-lb/$\sqrt{W}$ and a ripple torque of about 4 percent. The maximum torque available from each is 11 ft-lb. The tachometers have a sensitivity of 0.48 V/rad/s and a 1-percent ripple voltage.

Motor position is measured using an incremental optical encoder with a home position indicator. The encoders for the experiment are Dynamics Research Corporation model C25 with 3,000 counts/rev. An IXYS IXSE502 encoder interface IC reduces the overhead of the microcontroller by performing a quadrature evaluation of the encoder signals. This increases the overall encoder pulse count to 12,000 counts/rev resulting in a resolution of 0.524 mrad or 1.8 arcmin.

A control system block diagram for the RUM servo is shown in figure 5. A constant incremental angle is commanded every T = 5 ms, resulting in a constant rate of rotation. For compatibility, the commanded value entered into the microcontroller is chosen to be an integer multiple of the incremental encoder quantization. To properly generate circular scans, the two RUM devices need to be 180° out of phase with each other. This is accomplished by initially positioning the RUM's and then commanding the same incremental angles to each device. Feed-forward compensation is used to cancel the disturbance torque due to gravity acting on the RUM mass before it produces a rate and angle error.

Control system block diagrams for the cross-elevation and elevation servos are shown in figures 6 and 7, respectively. Their function is to keep the scan centered on the target. Rate feedback is required from the tachometers for control of both gimbal axes. The tachometer outputs are filtered by 40-Hz analog low-pass filters before being sampled by 10-bit A/D converters in the microcontroller. The A/D converters are scaled to a range of ±0.35 rad/s or ±20°/s. To measure the gimbal angles, the gimbal encoder outputs are also sampled every 5 ms and summed in the microcontroller. In order to synchronize the gimbal servos with the RUM servos, the commands to the gimbal servos are generated from the RUM servo commands and the ideal scan parameters. The elevation servo differs from the cross-elevation servo only in the input commands.

The control gains for the RUM servos were chosen for a 5-Hz unity gain crossover frequency, and those for the gimbal servos were chosen for 0.25 Hz. These were arrived at by simulation, subject to the condition that they be separated by a factor of 10 or more to prevent the possibility of any cross coupling between the servos. In order to achieve excellent results, the sampling rate for the sensors was chosen to be 200 Hz (i.e., 5 ms) which is more than a factor of 10 above the unity gain crossover frequency for the RUM servos. For these design specifications, the RUM servo control gains were determined to be:

$$k_R = 6{,}500.0 \text{ s}^{-2}$$

$$k_P = 260.0 \text{ s}^{-2}$$

$$k_I = 2.6 \text{ s}^{-2}$$

$$\hat{I}_R = 0.03875 \text{ slug-ft}^2 ,$$

and the control gains for the gimbal servos were determined to be:

$$k_R = 15.7 \text{ s}^{-1}$$

$$k_P = 1.59 \text{ s}^{-1}$$

$$k_I = 0.00125 \text{ s}^{-1}$$

$$\hat{I}_X = \hat{I}_E = 16.3 \text{ slug-ft}^2 .$$

Finally, the torque motor commands for the gimbal servos are passed through a 40-Hz digital low-pass filter before the PWM commands are generated. This helps attenuate any higher frequency noise in the gimbal servos. The digital filter parameters were calculated to be :

$$a = 0.285$$

$$b = 0.715 .$$

IV. COMPUTER SIMULATION OF THE TOTAL SYSTEM

A computer model of the system was developed to verify the servo designs and make an assessment of system performance. The plant is modeled using simple rigid-body dynamics. The torque motor models include torque ripple and brush friction. The latter is simulated by a Dahl friction model with a running friction of $T_F = 0.25$ ft-lb. The quantization associated with the system's sensors and motors is also included, as well as the sample rate of the sensors and computation cycle of the microcontroller.

Figure 8 shows a circular scan centered about $\theta_E = \theta_X = 0$ rad, or 0°, that was generated by the computer model. To achieve this, the sinusoidal commands shown in figures 6 and 7 were issued to the gimbal servos. These had an amplitude of $\theta_{XM} = 0.024$ rad, or 1.4°, and a frequency of 1 Hz. The rotation rates of the RUM devices are shown in figure 9. The RUM's were initially at rest and then commanded to a rate of $\Omega_R = 6.28$ rad/s, or 1 Hz, to generate the scan. The torque motor outputs for the RUM devices are shown in figure 10. The peak torque is 2.75 ft-lb. Figure 11 shows the gimbal torques, which keep the scan centered and counter gimbal friction. At steady state, the peak value is 0.5 ft-lb in each axis. Figure 12 shows the gimbal angle error signals. At steady state, the peak error is 0.001 rad, or 0.06°, in each axis.

These simulation results can be used to estimate the power savings realized by using the RUM devices for scanning, as opposed to scanning solely with the gimbal torquers. With a motor constant of 0.61 ft-lb/$\sqrt{\text{W}}$, the peak power for scanning with the RUM devices is calculated to be:

$$P_M = 2 \cdot (2.75/0.61)^2 + 2 \cdot (0.5/0.61)^2 = 42 \text{ W}.$$

For comparison, this same case was simulated using only the gimbal servos to perform the scan motions without activating the RUM's. To accomplish this, it was first necessary to increase the maximum torque from the gimbal torquers from 11 ft-lb to 22 ft-lb to prevent torque saturation while scanning. The simulation results are shown in figures 13 through 15. Figure 13 shows the circular scan profile and figure 14 presents the gimbal torques. Observe that the peak torque in each axis is now 16.0 ft-lb, as opposed to 0.5 ft-lb before. The gimbal angle error signals are shown in figure 15. Observe that the peak error signal in each axis is now 0.009 rad or 0.52°, compared to 0.001 rad or 0.06° before. Therefore, scanning without the RUM's increases the peak torque by a factor of 32 and the peak error signal by a factor of 9, in each axis. The peak power for this case is:

$$P_M = 2 \cdot (16.0/0.61)^2 = 1{,}376 \text{ W} .$$

Thus, when comparing the peak powers for scanning in a one-g environment, the RUM devices are 33 times more efficient. Furthermore, because the gravity torque is zero in a one-g environment at ±90° elevation angle or in a zero-g environment, using the RUM devices for scanning reduces the power required by a factor of 688. Table 1 presents the power requirements for each scenario.

Table 1. Peak power required for scanning.

Conditions	RUM's+Gimbals (W)	Gimbals Only (W)
1-g Environment/ 0° Elevation Angle	42	1,376
1-g Environment/ ±90° Elevation Angle	2	1,376
0-g Environment/ All Elevation Angles	2	1,376

V. CONCLUSIONS

The RUM experiment configured for circular scanning is very similar to that for line and raster scanning. Only, the RUM devices are mounted differently and the software algorithms that generate the servo commands are slightly different. According to the computer simulation results, when the RUM experiment is reconfigured to perform circular scans, it executes circular scanning as effectively as it does line and raster scanning. Hence, the RUM experiment can easily be configured to simulate circular, line, and raster scanning in zero-g and one-g environments. While simulating circular scanning in the worst-case orientation of one-g, the simulation results presented here show that the power required is 33 times less when the RUM devices produce the scan motion. With line and raster scanning, it was found to be 16 times less.

The plan for the future is to build the RUM experiment for line and raster scanning and do this testing first. Scanning will be done with and without the RUM devices in simulated zero and one-g environments. When this is finished, the RUM experiment will be reconfigured for circular scanning and similar testing performed for circular scanning. Results from the actual experiment will be compared with those from simulation in assessing the performance of the RUM devices for scanning gimbaled payloads. Inferences about scanning free-flying spacecraft with and without the RUM devices scan will also be made.

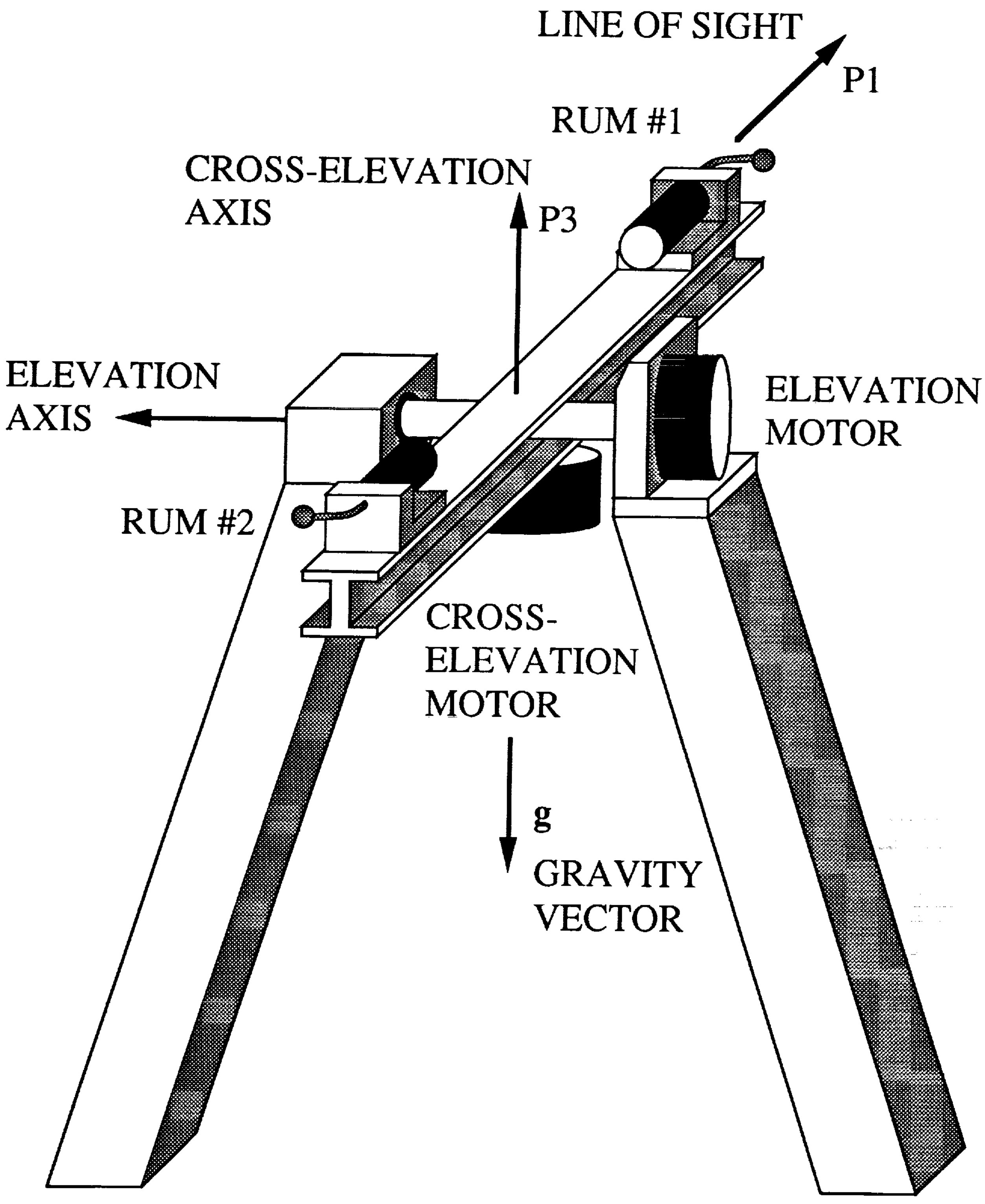

Figure 1. Rotating unbalanced-mass (RUM) mechanical configuration.

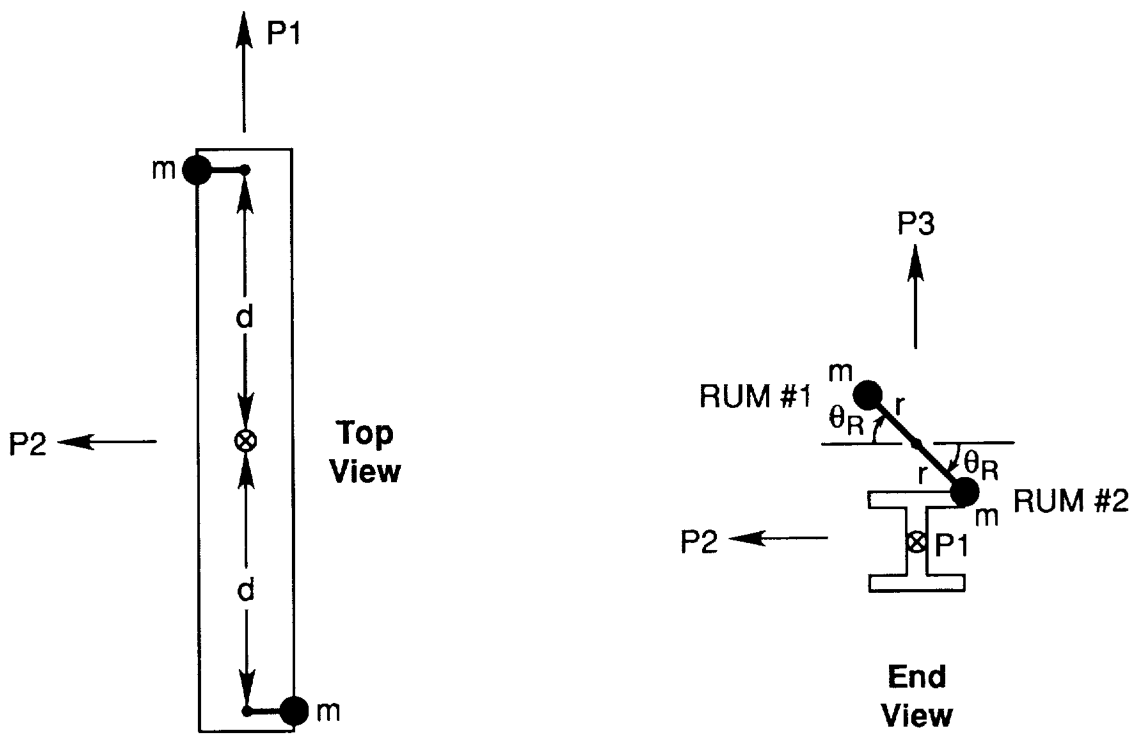

Figure 2. Definition of the RUM parameters.

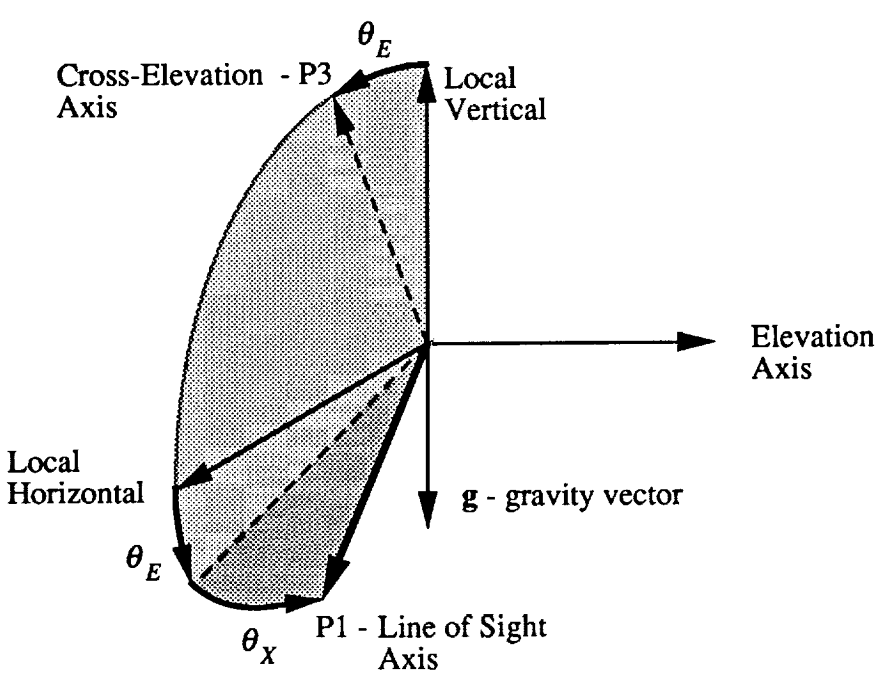

Figure 3. Gimbal angles in relation to the gravity vector.

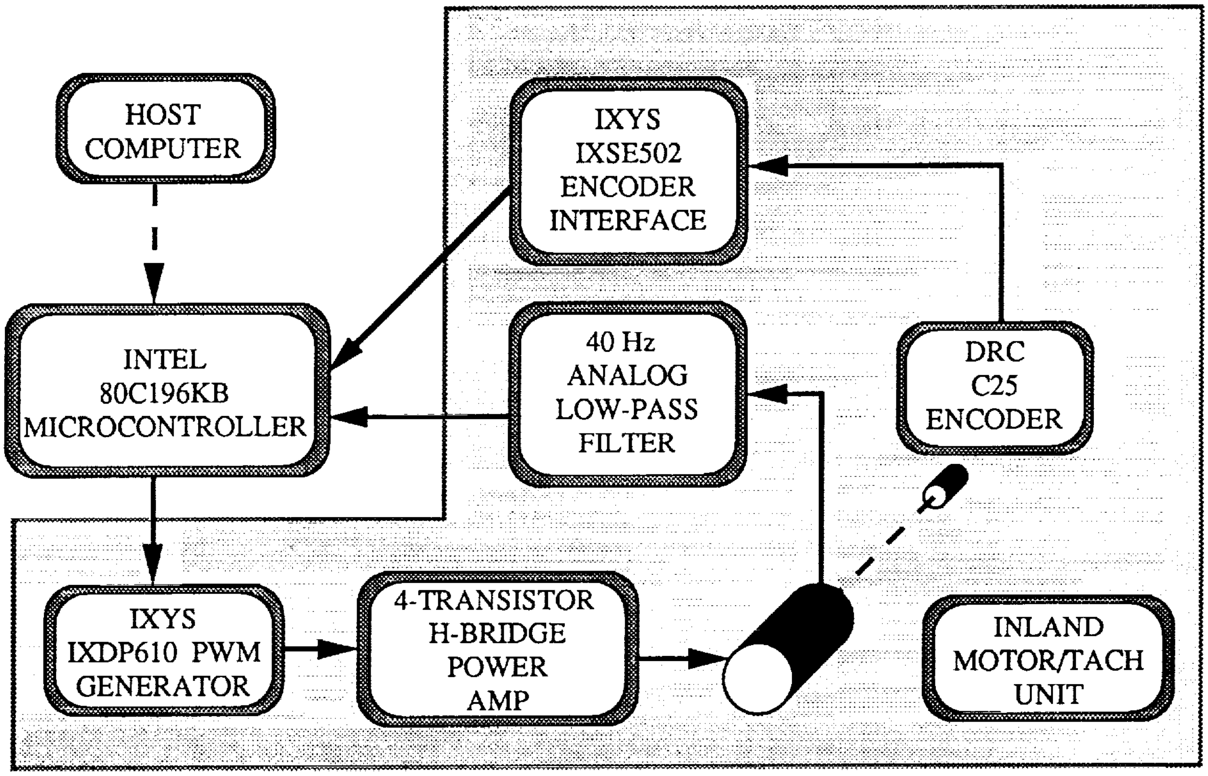

Figure 4. Servo electronic-hardware block diagram.

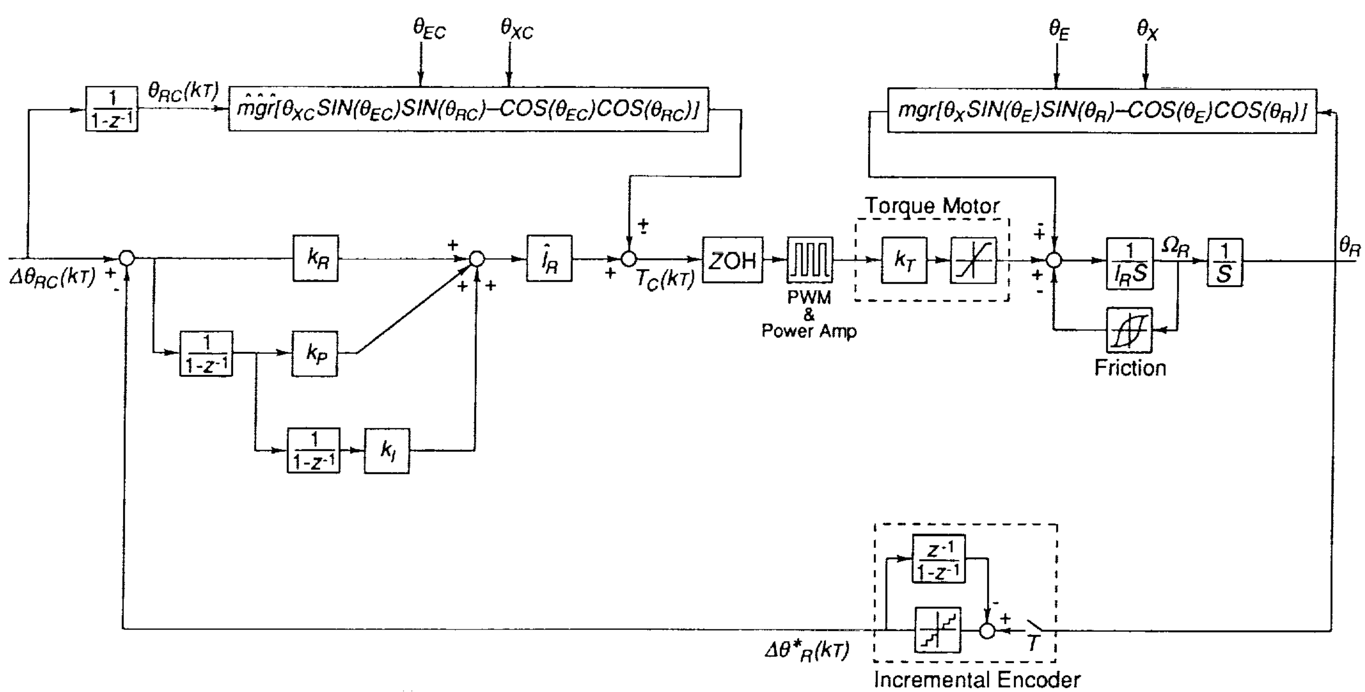

Figure 5. Control system block diagram for the RUM servos.

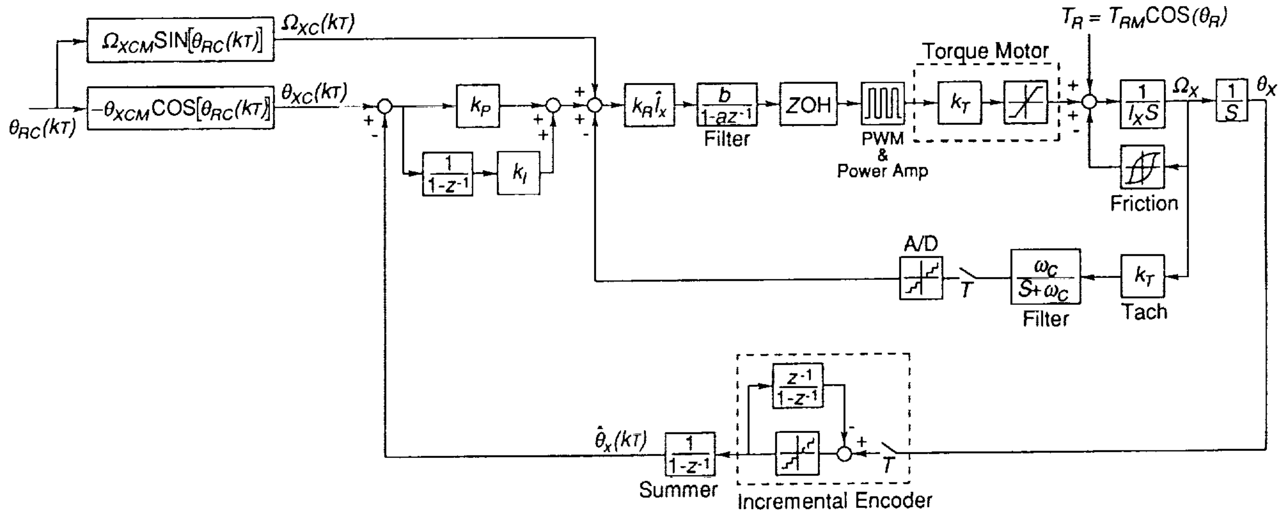

Figure 6. Control system block diagram for the cross-elevation servo.

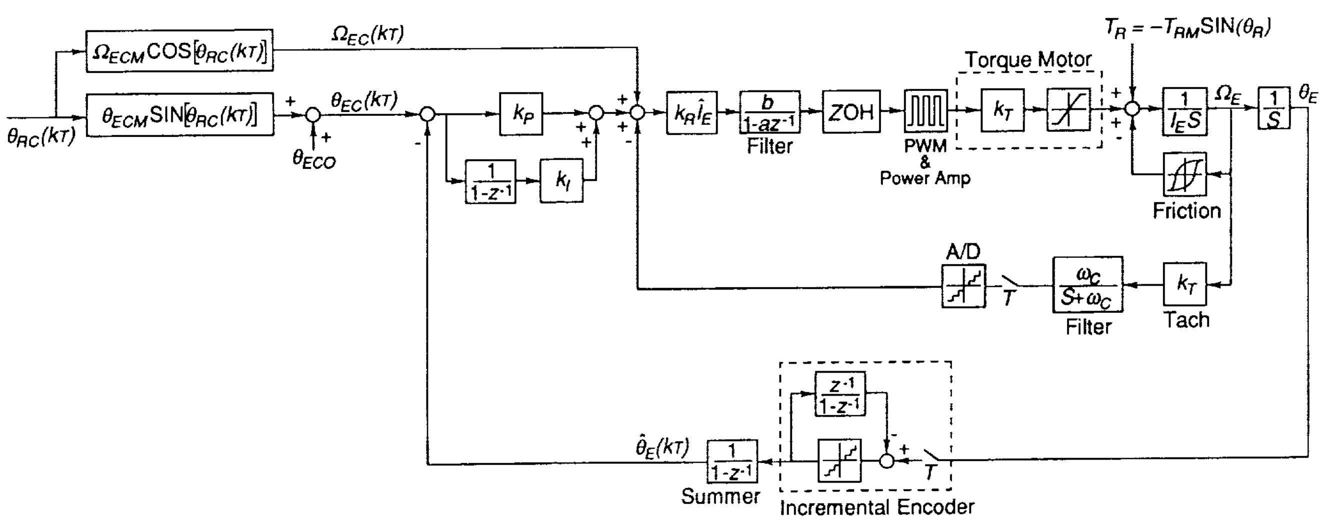

Figure 7. Control system block diagram for the elevation servo.

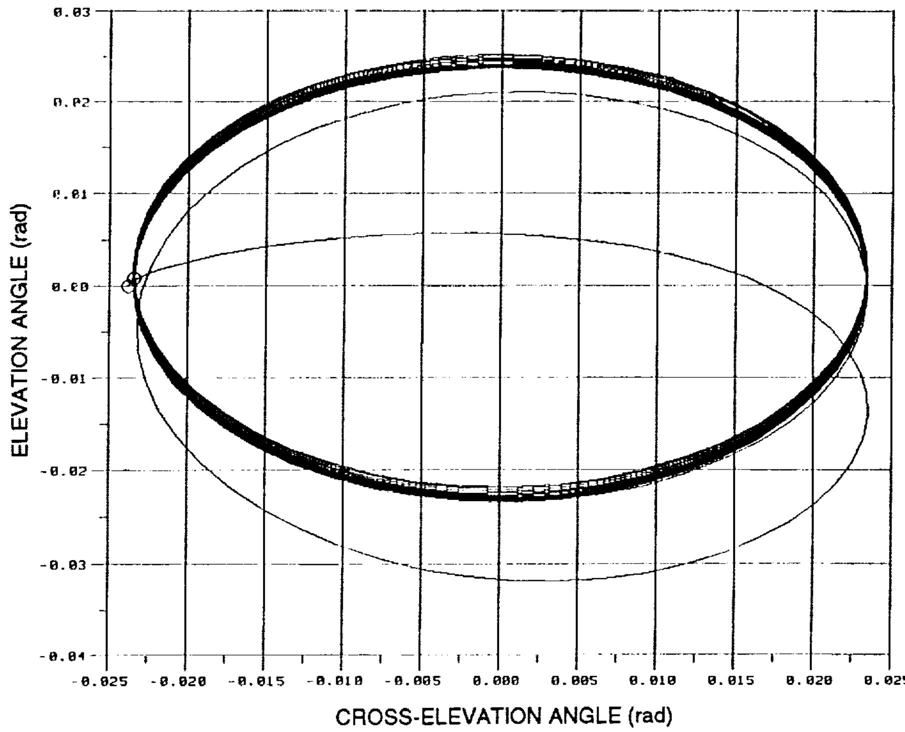

Figure 8. Circular scan profile scanning with RUM's and gimbal servos.

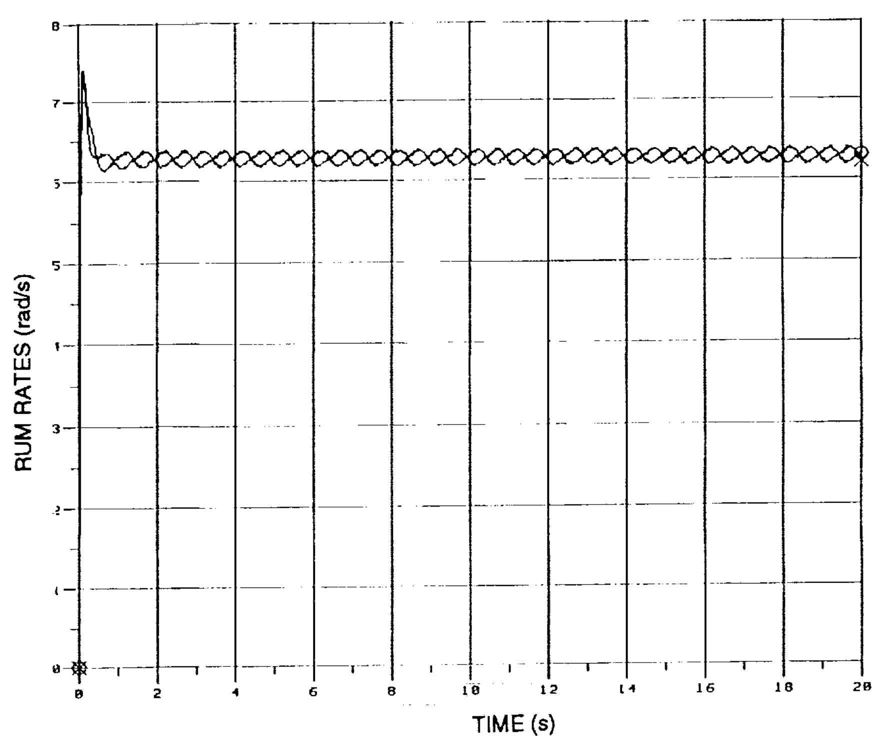

Figure 9. RUM rates scanning with RUM's and gimbal servos.

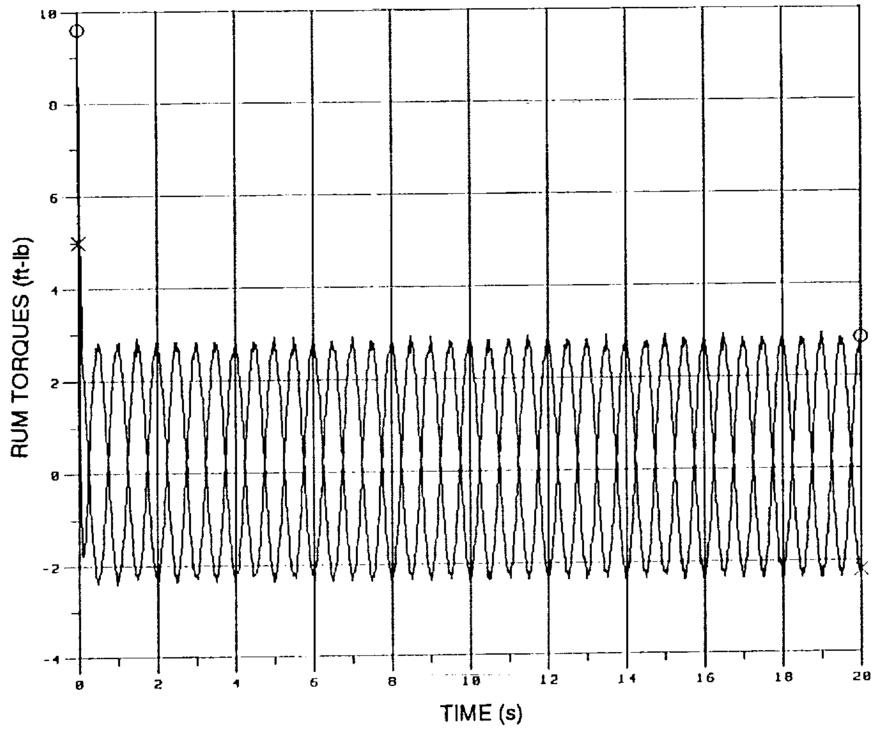

Figure 10. RUM torques scanning with RUM's and gimbal servos.

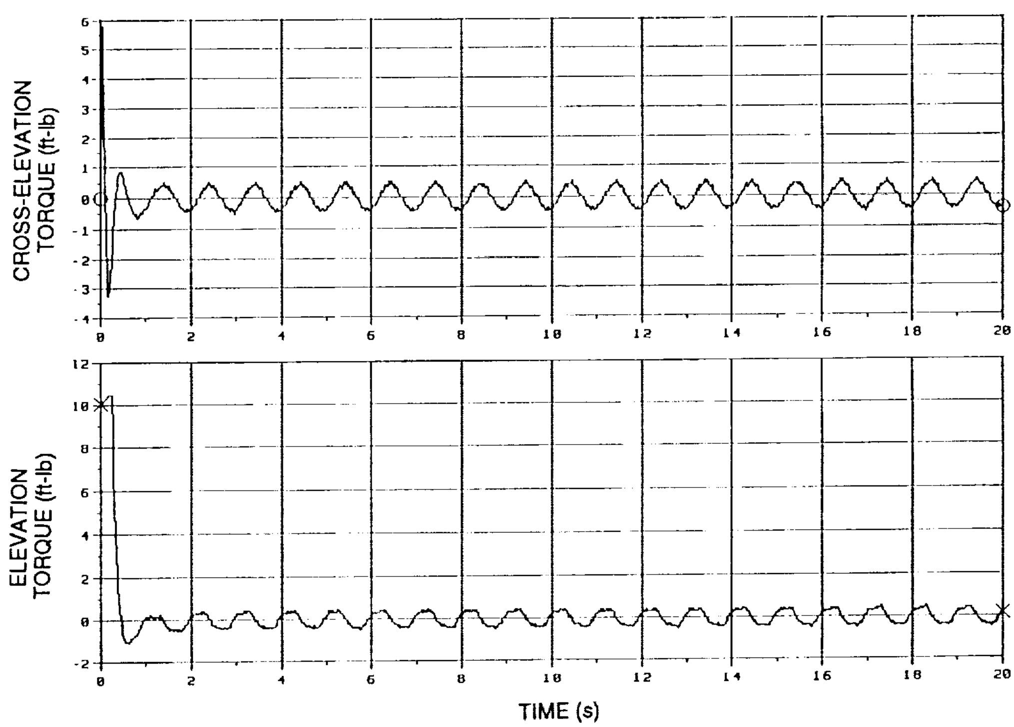

Figure 11. Gimbal torques scanning with RUM's and gimbal servos.

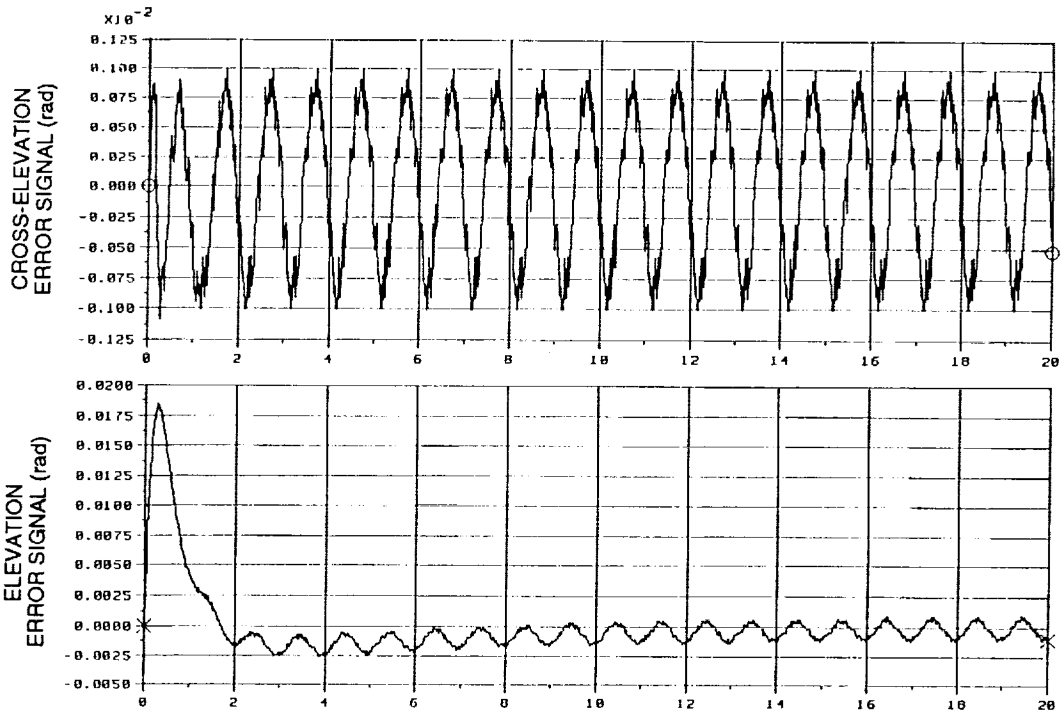

Figure 12. Gimbal error signals scanning with RUM's and gimbal servos.

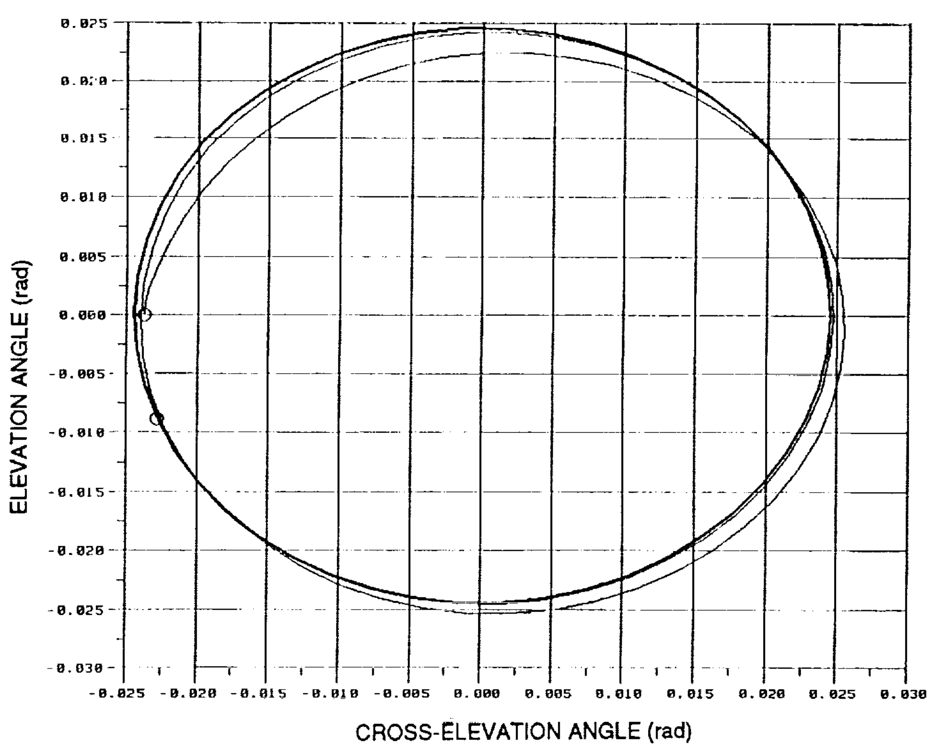

Figure 13. Circular scan profile scanning with gimbal servos only.

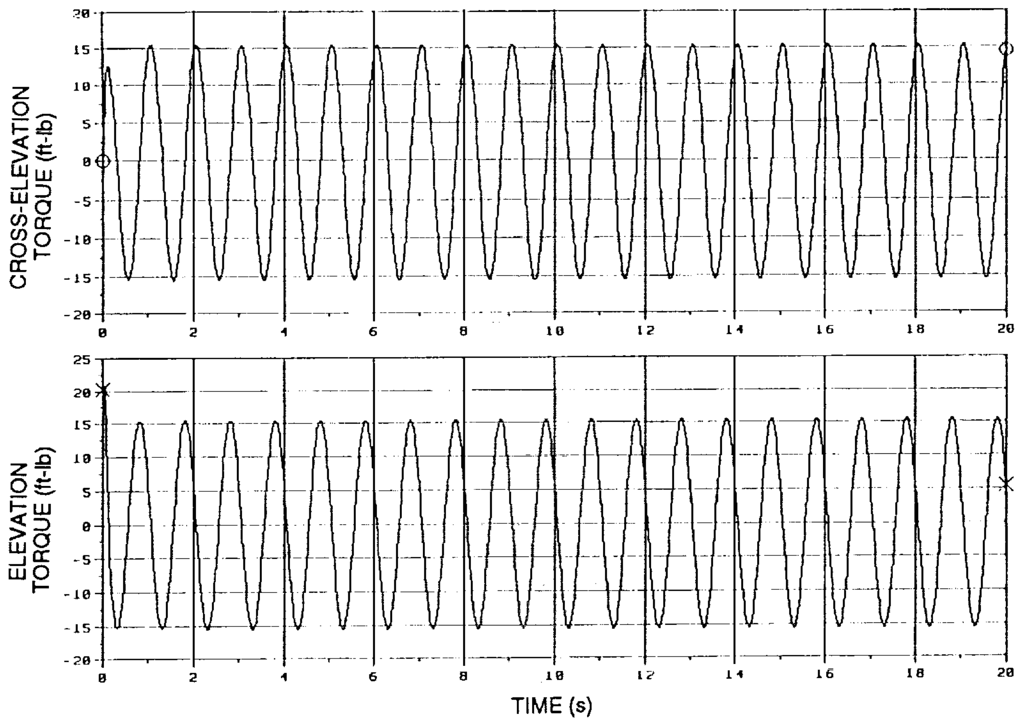

Figure 14. Gimbal torques scanning with gimbal servos only.

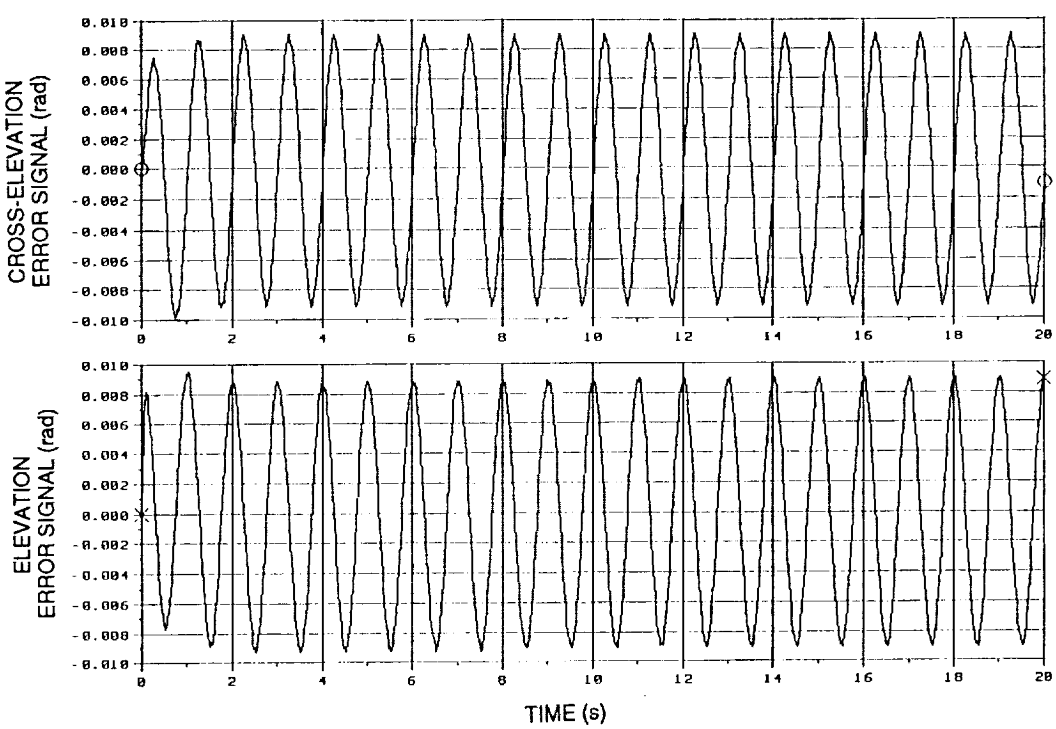

Figure 15. Gimbal error signals scanning with gimbal servos only.

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5. Lightsey, W.D., Alhorn, D.C., and Polites, M.E.: "Definition and Design of an Experiment to Test Raster Scanning With Rotating Unbalanced-Mass Devices on Gimbaled Payloads." NASA TP-3249, NASA Marshall Space Flight Center, AL, June 1992.

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13. ABSTRACT *(Maximum 200 words)*

This paper describes a ground-based experiment designed to prove the concept of circular scanning a gimbaled payload with rotating unbalanced-mass (RUM) devices. The experiment is a modified version of a similar experiment which demonstrates line and raster scanning with RUM's. In this paper, a description of the experiment hardware is presented and a detailed design of the servos used in scanning is given. A computer simulation model of the entire system is discussed and simulation results are included. These verify the servo designs and show the RUM's to be an extremely power efficient method for circular scanning.

14. SUBJECT TERMS

Free-Flying Spacecraft, Gimbaled Payloads, Circular Scanning, Line Scanning, Raster Scanning, Rotating Unbalanced-Mass Devices

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